2018

The effect of hip abductor weakness in different patient populations

BOSTON UNIVERSITY

SCHOOL OF MEDICINE

Thesis

THE EFFECT OF HIP ABDUCTOR WEAKNESS IN DIFFERENT PATIENT POPULATIONS

by

MARGARET ELIZABETH JONAS

B.A., Princeton University, 2014

Submitted in partial fulfillment of the

requirements for the degree of

Master of Science

2018

Approved by

First Reader ____

Cara Lewis, PT, Ph.D.
Associate Professor, Department of Physical Therapy & Athletic Training and Department of Health Sciences

Second Reader ____

C. James McKnight, Ph.D.
Associate Professor of Physiology and Biophysics

ACKNOWLEDGMENTS

I would like to thank Dr. Lewis for giving me the opportunity to dive into the research done on the hip abductor muscles and gait mechanics. Thank you to Dr. Jamie McKnight and Dr. Gwynneth Offner for their unwavering support throughout my time in the Master's Program at BU. Thank you to my classmates in the Master's in Medical Sciences program who have inspired me to become the best student I can be, and to the Heartbreakers for providing both a practical application for my literature studies and a physical outlet when I needed an outlet from the library.

THE EFFECT OF HIP ABDUCTOR WEAKNESS IN DIFFERENT PATIENT POPULATIONS

MARGARET ELIZABETH JONAS

ABSTRACT

The Gluteus Medius and the Tensor Fascia Lata are two of the main muscles involved in the action of hip abduction. This action is important for both dynamic movements in athletic pursuits and in every day ambulation. Weakness in these muscles has been connected to multiple injuries in the lower limb, but the question of the casual relationship between gait change, hip abductor weakness, and lower limb injury is still up for debate. As presented by the current research, younger populations tend to have overuse injuries with females having a greater susceptibility for injuries connected to hip abductor weakness, and older populations tend to have injures related to atrophy and degeneration of either the hip abductor muscles or the joint surrounding the hip. Research in this field has increasingly focused on sub-sets of the populations, such as just females or just males, trying to pinpoint the role that hip abductor weakness plays in these injuries. By trying to minimize or even eliminate the confounding variables that have previously made it difficult to determine the role hip abductor weakness plays in these gait changes and injuries, these studies have been able to make more clear conclusions at the expense of making a broader generalization. Similarities and differences between how the sub-groups present with hip abductor weakness are discussed, as well as discrepancies observed within the research done on similar cohorts. Future directions for

research in this field are discussed, as well as implications for clinical implementation of targeted rehabilitation programs to ensure the best possible outcomes.

TABLE OF CONTENTS

TITLE……………………………………………………………………………...i

COPYRIGHT PAGE……………………………………………………………...ii

READER APPROVAL PAGE…………………………………………………..iii

ACKNOWLEDGMENTS iv

ABSTRACT v

TABLE OF CONTENTS vii

LIST OF TABLES ix

LIST OF FIGURES x

LIST OF ABBREVIATIONS xi

INTRODUCTION 1

Specific Aims 5

PUBLISHED STUDIES 6

Studies Focused on Younger Populations 7
Studies Focused on Older Populations 13
Females with Hip Abductor Weakness 18
Males with Hip Abductor Weakness 22

DISCUSSION 27

Points of injury in males versus females 28
Hip OA and other pathologies of the hip in younger versus older populations 34

CONCLUSIONS AND FUTURE DIRECTIONS 36

REFERENCES 39

CURRICULUM VITAE 46

LIST OF TABLES

Table	Title	Page
1	List of Studies on Younger Populations with ITBS	8
2	List of Studies on Older Populations	14
3	Body Mass Index Classification According to the World Health Organization	17
4	Frequency and Sex Distribution of the 26 most common injuries	18
5	Mean baseline characteristics for the most common injuries	19
6	Studies focusing on females with PFPS	20
7	Studies focusing on males with hip abductor weakness	23

LIST OF FIGURES

Figure	Title	Page
1	Variations in the locations of the bony proximal and distal insertion sites of GMed	2
2	The marker set-up used to track motions at the pelvis, femoral region, and tibial region	11
3	Posterior view of the gluteal region	31
4	Lateral view of the leg	32

LIST OF ABBREVIATIONS

BMI…………………………………………………………..………….Body Mass Index

BU .... Boston University

DDH………………………………………..……..Developmental Dysplasia of the Hip

FAI…………………………………………………….Femoroacetabular Impingement

GMax………………………………………………………………….Gluteus Maximus

GMed……………………………………………………………..…..Gluteus Medius

GT………………………………………………...Greater Trochanteric Pain Syndrome

ITBS………………………………………………………..…..Iliotibial band syndrome

OA……………………………………………………………………….Osteoarthritis

PFPS……………………………………………...……Patelofemoral Pain Syndrome

TFL……………………………………………………………..Tensor Fascia Lata

INTRODUCTION

This thesis serves to discuss the hip abductor muscles, specifically the Gluteus Medius (GMed) and the Tensor Fascia Lata (TFL). This will examine the differences in both presentation and effect of weakness in different subsets of the population, with regards to a patient's age and sex. This introduction will serve to describe some of the current knowledge of the anatomy and functions of the hip abductors, specifically the GMed and the TFL. Additionally, some of the current research on resulting effects of hip abductor weakness will be presented as well.

Currently, there have been efforts to more specifically define the anatomy of the GMed. Cadaver studies have shown that the GMed has distinct compartments with each compartment having a separate innervation, which functionally translates to the muscle having more actions on the hip than just abduction, yet the number of compartments and the innervation patterns are not consistently noted (Gottschalk et al. 1989). In fact, a systemic review of anatomy texts notes conflicting reports on insertion sites, innervation patterns, and number of distinct compartments (Flack et al., 2012). **Figure 1** illustrates the discrepancies that different texts provide as to the location of insertion sites.

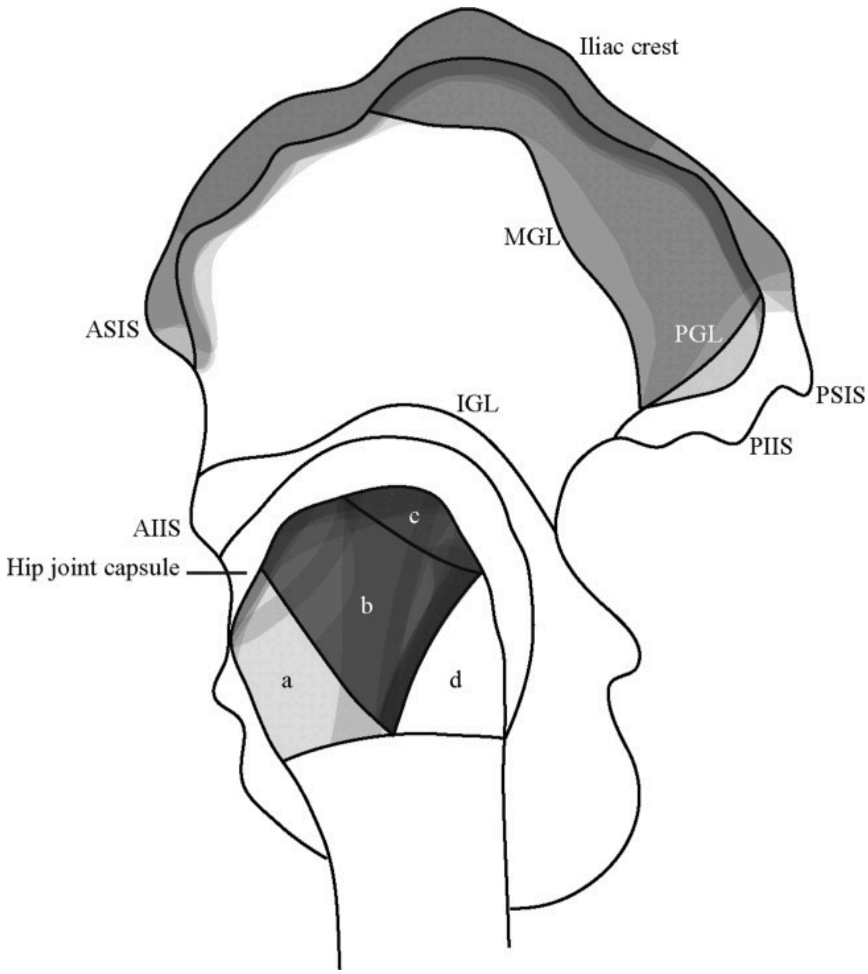

Figure 1. Variations in the locations of the bony proximal and distal insertion sites of GMed. Shaded areas note sites of bony insertion onto the ilium and the greater trochanter as described in anatomical texts and articles. Taken from (Flack et al., 2012)

The TFL, on the other hand, is a single-compartment muscle lying laterally between two layers of the fascia lata, and its innervation and role in hip abduction are generally described consistently (Flack et al., 2012). These discrepancies in the description of the anatomy and innervation of the GMed have led to more cadaver studies, and while the exact number of compartments in this muscle is still unclear, the presence of separate compartments falls in line with the idea that the GMed is responsible for actions including, but not limited to, hip abduction (Flack et al., 2014). The GMed is also associated with securing the pelvis over the stance leg to prevent pelvic drop on the contralateral side during waking and running, and with rotating the thigh medially (Drake, Vogl, & Mitchell, 2012).

With the GMed covering multiple actions including hip abduction, and TFL being of relatively small size in comparison to muscles surrounding it these two muscles are at risk for weakness (Flack et al., 2014). Whether that weakness is the cause of some downstream effects, or whether it occurs as a residual effect of another hidden cause, is still up for debate. One study done in 2000 demonstrated a correlation between weaker hip abduction strength and resulting iliotibial band syndrome (ITBS), as subjects diagnosed with ITBS showed decreased hip abductor torque as compared to the uninjured control group (Fredericson et al., 2000). Contrastingly, a study on a similar cohort, concluded that hip abductor weakness was not an important factor in the presentation of ITBS (Grau et al., 2008), which complicates the potential for using hip abductor weakness for early diagnosis and prevention of ITBS. Neither of these studies examined nor ruled out weakness in other thigh muscles as a potential indicator for ITBS.

Another theory addressing the hip abductors' role in these lower limb injuries looks at asymmetry in hip abduction strength rather than generalized weakness. Recently, studies focused on hip abductor asymmetry as an indicator for ipsilateral patellofemoral pain syndrome (PFPS) showed that patients who presented with early signs of PFPS or diagnosed PFPS showed no significant reduction in strength, less asymmetry than controls, stronger strength scores in the affected limb than the weaker limb of the controls, and no change in flexibility (Piva et al., 2005, Plastaras et al., 2016). Also, patients with diagnosed PFPS demonstrated decreased flexibility in the hamstrings, quadriceps, gastrocnemius, and soleus: muscles that are not primarily associated with hip abduction (Piva et al., 2005). These findings should lead to further examination of what is considered a potential indication of early PFPS. The 2016 study did not measure other muscle group strength and activation patterns during the exercises, so other sources contributing to the development of PFPS need to be examined more closely (Plastaras et al., 2016). More specifically, in order to consider whether hip abductor weakness is the cause of PFPS and other lower limb dysfunctions, analyses should be done on the whole limb's mechanics, and measurements should be taken on the strength of multiple muscles in the region rather than a small group of muscles responsible for a limited number of actions.

Specific Aims

The goal of this thesis is to compile the research done related to the hip abductor muscles – specifically the GMed and the TFL – to see if there are associated injury patterns within certain populations when hip abductor weakness or asymmetry is present. Specifically, this will examine if hip abductor weakness manifests itself differently based on age or between males and females. The distinctions in presentation and likelihood of injury could be helpful for creating more targeted treatment regimens and prescribing preventative measures for these patients return to normal activities.

PUBLISHED STUDIES

Hip abductor weakness can present itself in many ways depending on a patient's age or sex. The research is then guided by the clinical presentation secondary to said weakness rather than presenting with weakness first before other symptoms or syndromes arise. Therefore, division of patients in these studies is mainly done retrospectively when examining weakness. Additionally, most studies either specify which hip abductor muscles are being measured for weakness or they quantify weakness in the action of hip abduction as a whole. By measuring a specific muscle, studies are able to pinpoint which muscle is quantifiably weaker than either the unaffected side or the control group's muscle. However, using these results to make the conclusion that the subject is weaker in overall hip abduction is a stretch because not all muscles involved in the action are measured. Conversely, when measuring action weakness as a whole, either by observing a decrease in overall intensity or duration of force produced, it is easy to observe if there is a decrease in overall force, but the distribution of the production of the force is not known; it is possible that one muscle of the group could be producing more force than normal in order to compensate for another muscle producing substantially less force. The change in the distribution of force production rather than weakness in one muscle could either be the cause or the effect of certain injuries, but currently the research is still unclear.

Often, when one muscle is unable to produce enough force for an action, other muscles surrounding the joint will be recruited to contribute to that action. Therefore, many times in EMG studies will measure multiple muscles simultaneously in order to more accurately determine weakness in the overall action (Bailey et al., 2018; Barbosa et al., 2016; Bolgla et al., 2011). However, the EMG measuring capabilities are limited to only a few muscles at a time, and as a result some muscles might either get generalized to one probe where it may be beneficial to have multiple measurements for different compartments of the muscle, or some muscles might not get measured at all (Barbosa et al., 2016; Bolgla et al., 2011). The following four sections will outline the findings in studies focused on a either a younger or older population and studies focused on either males or females.

Studies Focused on Younger Populations

More studies have been done on younger populations with weak hip abductor muscles, and the most common injuries are due to overuse (Taunton et al., 2002). Namely, ITBS and PFPS are of particular interest when studying younger populations because these individuals tend to be more active (Taunton et al., 2002). The goal of addressing the role of hip abductor weakness in younger populations is to create effective rehabilitation programs that can allow patients to return to their athletic activities, which require more muscle strength and coordination than every-day tasks (Osborne et al., 2012).

The studies linking hip abductor weakness to ITBS present conflicting evidence, as seen in **Table 1**.

Table 1. List of Studies on Younger Populations with ITBS

Source & Publication date	Title	Gender	Population Age	Sample Size	Results
Brown et al., 2016	The effects of fatigue on lower extremity kinematics, kinetics and joint coupling in symptomatic female runners with iliotibial band syndrome	Females	Ages 19-47	32 (20 uninjured, 12 injured)	No significant difference between groups in hip abduction strength after fatigue
Foch et al., 2015	Associations between iliotibial band injury status and running biomechanics in women	Females	Ages 18-45	27 (total participants)	No strength differences found between injured runners vs. controls
Fredericson et al., 2000	Hip abductor weakness in distance runners with iliotibial band syndrome	Mixed	Ages 18-41	54 (24 injured, 30 controls)	Runners with ITBS have weaker hip abductors on the affected side compared to their unaffected side & have weaker hip abductors overall compared to uninjured runners
Grau et al., 2007	Hip Abductor Weakness is not the Cause for Iliotibial Band Syndrome	Mixed	Ages 18-50	20 (10 ITBS, 10 control)	No significant difference between injured vs. controls in hip abduction strength
Hamill et al., 2008	A prospective study of iliotibial band strain in runners	Females	Ages 18-45	34 (17 ITBS, 17 control)	Runners with symptoms do experience greater ITB strain
Noehren et al., 2014	Assessment of Strength, Flexibility, and Running Mechanics in Males with Iliotibial Band Syndrome	Males	Ages 18-45	34 (17 ITBS, 17 control)	No hip abduction strength differences found between injured runners vs. controls

Several studies cite hip abductor weakness as a risk factor for ITBS, citing that runners who present to clinic with weaker hip abductor muscles show a higher rate of IT band strain and are at a higher risk for developing ITBS (Fredericson et al., 2000; Hamill et al., 2008). According to the American Academy of Family Physicians, ITBS occurs when the iliotibial band is impinged by the lateral femoral condyle. This causes a person to feel pain laterally on the hip joint, and is often felt while running, but only after running for a period of time (Fairclough et al., 2006; Arnold & Moody, 2018). Over time, the onset of lateral pain will occur sooner during running, and in more severe cases, the pain does not subside during rest (Arnold and Moody, 2018).

Runners with ITBS have shown to make significant strength improvements when given short-term rehabilitation protocols that target strengthening the GMed (Fredericson et al., 2000; Barbosa et al., 2016). However, in both Hamill et al., and Fredericson et al., the TFL involvement was either excluded or not measured in evaluating the hip abduction strength and strain rate, which given the fact that the TFL's primary action is hip abduction, makes it difficult to generalize the benefits onto the entire group of muscles when one of those muscles was not accounted for (Flack et al., 2012).

Other studies examining the relationship between hip abductor weakness and ITBS have not found as strong of a correlation between the two. Isometric strength measurements of the hip abductor muscles between subjects with ITBS and without ITBS show no significant strength difference between the injured and non-injured limb (Grau et al., 2007). Furthermore, several studies have demonstrated that though subjects with ITBS do not exhibit decreased hip abduction strength with fatigue or injury, but they do exhibit altered running mechanics with ITBS. The altered mechanics range from increased trunk flexion ipsilaterally, decreased peak hip adduction angle, or increased hip internal rotation angle and knee adduction (Noehren et al., 2014; Foch et al., 2015; Brown et al 2016). In either case, motion recordings were captured via 3-dimensional motion tracking with reflective markers. Depending on what motions the study focused on, the markers were placed accordingly. The various differences in gait mechanics observed and potentially attributed to hip abductor weakness could be due to differences in marker placement. **Figure 2** shows the marker placement in Brown et al. study.

Figure 2. The marker set-up used to track motions at the pelvis, femoral region, and tibial region. Taken from (Brown et al., 2016)

The most common overuse injury seen in younger populations, regardless of sex, is PFPS (Taunton et al., 2002). Many studies have recorded hip abductor weakness in subjects with diagnosed PFPS, by noting that injured subjects generated less peak abductor force than their uninjured counterparts (Baldon et al., 2009; Boling et al., 2009; Cichanowski et al., 2007; Ireland et al., 2003; Nunes et al., 2018). However, in cases where subjects are demonstrating the early signs of PFPS, no difference in hip abductor strength was observed, so the hip abduction weakness could have been a result of the PFPS rather than one of the causes (Plastaras et al., 2015). Also, it has been shown that while there are differences in the flexibility of the quadriceps, hamstrings, gastrocnemius, and soleus, in patients with PFPS, the structure of the TFL and the surrounding complex are not significantly different between those with ITBS and controls (Piva et al., 2005).

All of the aforementioned studies sampled either a majority female or an entirely female population and though the occurrence of PFPS has been observed to be more frequent in females, knowing that males and females demonstrate different activation patterns during motion, it could be possible that PFPS presents itself more in females due to differences in muscle activation patterns rather than weakness of the muscle group (Taunton et al., 2002; Flaxman et al., 2013).

With regards to muscle activation pattern differences between subjects with ITBS and uninjured controls, studies have found either an increase in the projection angle of the knee, decreased trunk lateral flexion, combined with decreased hip abduction and hip external rotation, and an increase in hip adduction (Leão et al., 2016; Willson et al., 2009; Dierks et al., 2008). Separately, these movement differences are minor, but when these deviations occur all at once in the same injury pattern, it is difficult to assess if hip abductor weakness is the first and foremost cause of these changes, or if it is one of the downstream effects of the change.

Studies Focused on Older Populations

In older populations, it is common to see pathologies such as Greater Trochanteric Pain (GT), and Hip Osteoarthritis (OA) (Aepli- Schneider et al., 2012; Fearon et al., 2017; Zacharias et al., 2016). GT is diagnosed when there is tenderness to the touch over the greater trochanter area but swelling and inflammation are not present in the sensitive area. Often GT is associated with IT band pain, low back pain, and knee OA. GT greatly limits people in their ability to stand up from a chair, and slows a person's gait (Segal et al., 2007). Hip OA is a subset of osteoarthritis, which refers to joint pain and stiffness in the hip. Patients who develop hip OA have joint pain greater than 50% of the time, degeneration of cartilage at the hip joint, and often have hip joint space narrowing in X-ray studies. Hip OA is less common than other types of OA, and the progressive nature of the condition leads many people to seek surgery to alleviate the pain caused by the significant degeneration in the joint (Arden & Nevitt, 2006). The main studies focusing on older populations with hip abductor weakness are presented in **Table 2.**

Table 2. List of Studies on Older Populations.

Source & Publication date	Title of article	Gender	Population Age	Sample Size	Results
Aepli-Schneider et al., 2012	Degenerative rupture of the hip abductors	Females	Ages 58 through 83	4	All 4 subjects showed tears in the GMed or GMin tendon
Cooper et al., 2016	Prevalence of gluteus medius weakness in people with chronic low back pain compared to healthy controls	Mixed, more females	Average age was early 40s	225 (150 with LBP, 75 controls)	TFL & GMed in Low Back Pain group were weaker on the affected side as compared to the unaffected side & LBP group had weaker TFL and GMed than TFL & GMed in control group
Dwyer et al., 2013	Comparison of gluteus medius muscle activity during functional tasks in individuals with and without osteoarthritis of the hip joint	Mixed	Mean age = 51.1 (SD 2.3)	30 (13 hip OA + 17 control)	Patients with hip OA showed increased GMed activation during stair-climbing tasks compared to control group's activation patterns
Fearon et al., 2017	Pain, not structural impairments may explain activity limitations in people with gluteal tendinopathy or hip osteoarthritis: A cross sectional study	Females	Mean age was 50s-60s	79 (36 with GT, 20 with hip OA, and 21 control)	Both GT & hip OA had similar pain levels & weaker hip abductors bilaterally than asymptomatic controls
Zacharias et al., 2016	Hip abductor muscle volume in hip osteoarthritis and matched controls	Mixed	Ages 40+ (Mean 63.4)	40 (20 hip OA + 20 control)	Gluteal muscle atrophy, increased gluteal fatty infiltration and hip strength deficits were evident in the affected hips of OA participants as compared to the unaffected side and to the control groups' hip abductor muscles

Zacharias et al., 2018	Atrophy of hip abductor muscles is related to clinical severity in a hip osteoarthritis population	Mixed, more females	Ages 50+ (mean ages for each group was ~62)	40 (20 hip OA + 20 controls)	Muscle atrophy was identified in all 3 gluteus muscles in hip OA groups and degree of atrophy was associated with degree of OA severity; G-Med asymmetry only present in the moderate-severe hip OA group

The studies done on hip abductor weakness and its relationship to those pathologies are usually conducted populations who do not have any comorbid conditions (Dwyer et al., 2013; Zacharias et al., 2016). These exclusion criteria cause many of the older population samples to shrink rapidly, and the mean ages of most studies ends up reflecting a much younger population when trying to investigate the effect on a specific condition or injury pattern, making it difficult to assign these conclusions as applicable to the older individuals. As a result, the studies on older populations are often case studies or mixed in with younger individuals in order to produce a sample size with adequate power, yet there are still some interesting patterns that arise from the data.

For patients with unilateral hip OA, it has been shown that the muscle mass of the hip abductor muscles, is less than that of both the unaffected side and is less than that of age-matched controls. When examining each hip abductor muscle individually, it is shown that the GMed muscle mass is less than that of both the unaffected side and is less than that of age-matched controls, while there is no significant difference between affected patients' and controls' TFL muscle mass (Zacharias et al., 2016). Additionally, the degree of asymmetry between the affected and unaffected side is more pronounced in patients with hip OA as compared to the controls. Examining the data further, the higher grade the hip OA, the more pronounced the asymmetry and the larger decrease in muscle mass (Zacharias et al., 2016; Zacharias et al., 2018).

This decrease in muscle mass is hypothesized to correlate with an increase in muscle activation during dynamic and functional tasks, assuming that there is a negative-linear relationship between activation patterns and amplitude, and amount of muscle mass. And in fact, when examining the activation patterns and amplitudes of older individuals with hip OA, it has been demonstrated that the activation amplitude sent to the GMed is much greater than that of controls. This study concludes that the increased amplitude of activation is a compensatory mechanism for the decreased muscle mass and subsequent weakness (Dwyer et al., 2013). However, when projecting the same amplitude of a stimulus onto a smaller mass, one would think that the smaller mass would respond and not atrophy. It is possible that either the increased stimulus causes damage to the muscle, resulting in atrophy, or the muscle becomes desensitized to the stimulus and it atrophies as a result, but due to the cross-sectional design of this study, these theories were not investigated (Dwyer et al., 2013).

Low back pain is also another common ailment that has been connected to having weak hip abductor muscles (Bewyer et al., 2009; Cooper et al., 2016). While there are many factors that could cause low back pain, this study specifically the strength of the GMed, TFL, and the Gluteus Maximus (GMax) and its connection to patients with lower back pain (Cooper et al., 2016). This study, done retrospectively, found that there was a significant difference in GMed strength in patients with low back pain as compared to controls, but there was not a significant difference in TFL strength between the two groups (Cooper et al., 2016).

With this in mind, the results could point to GMed weakness as a predictor of low back pain, however the low back pain group had a mean weight that was 11.7 kg higher than the control group, and a mean BMI of 29.6 compared to the control group's mean BMI of 25.8. The difference in body mass index (BMI) between the injured and control groups was significant, to the point where the patients in the low back pain group were on the edge of the "Obese" classification and the controls were at the lower end of the "Overweight" classification, as seen in **Table 3** (Su et al., 2018).

Table 3. Body Mass Index Classification According to the World Health Organization

BMI	Classification
18.5–24.9	Normal Weight
25–29.9	Overweight
30–34.9	Obese
35–39.9	Severely obese
>40	Morbidly obese

Additionally, it has been demonstrated that BMI strongly correlates with increased risk of low back pain – even when controlling for risk factors, including but not limited to back OA and knee surgery – so it is more likely that GMed weakness is a minor downstream effect of the low back pain caused by some unknown source (Su et al., 2018).

Females with Hip Abductor Weakness

When looking at hip abductor weakness presentation differences based on sex, there are a few key points to note. It has been shown that overall females who run present with ITBS and PFPS more frequently than males, as seen in **Table 4**.

Table 4. Frequency and Sex Distribution of the 26 most common injuries

Injury	Men (n/%)	Women (n/%)	Total (n)
Patella femoral pain syndrome*	124/38	207/62	331
Iliotibial band friction syndrome*	63/38	105/62	168
Plantar facsiitis*	85/54	73/46	158
Meniscal injuries*	69/69	31/31	100
Tibial stress syndrome	43/43	56/57	99
Patellar tendinitis*	55/57	41/43	96
Achilles tendinitis*	56/58	40/42	96
Gluteus medius injuries*	17/24	53/76	70
Stress fracture—tibia	27/40	40/60	67
Spinal injuries	24/51	23/49	47
Hamstring injuries	25/54	21/46	46
Metatarsalgia	17/50	17/50	34
Anterior compartment syndrome	13/46	15/54	28
Gastrocnemius injuries*	19/70	8/30	27
Greater trochanteric bursitis	9/39	14/61	23
Adductor injuries*	15/68	7/32	22
Osteoarthritis (knee)*	15/71	6/29	21
Sacroiliac injuries*	2/10	19/90	21
Stress fracture—femur	6/32	13/68	19
Ankle inversion injuries	9/53	8/47	17
Iliopsoas injuries	6/37	10/63	16
Chondromalacia patellae	4/31	9/69	13
Peroneal tendinitis	9/69	4/31	13
Morton's neuroma	5/42	7/58	12
Abductor injuries	7/67	4/33	12
Calcaneal apophysitis	7/58	5/42	12
Tibialis posterior injury	8/73	3/27	11

*Significant sex difference at $p<0.05$.

In examining the data more carefully, the younger population of females are at greater risk for these overuse injuries as seen in **Table 5** (Taunton et al., 2002).

Table 5. Mean baseline characteristics for the most common injuries

	Age (years)	Height (cm)		Weight (kg)		BMI (kg/m²)		Activity history (years)	Weekly hours
		Men	Women	Men	Women	Men	Women		
PFPS	32.2	168.0	168.7	74.6	58.0	23.7	20.9	8.8	5.4
ITBFS	31.1	169.9	158.1	75.7	60.0	23.7	21.2	7.3	4.9
Plantar fasciitis	41.8	168.2	157.4	76.5	63.5	23.8	23.0	12.1	5.9
Meniscal injuries	43.2	170.1	156.7	80.6	61.9	25.0	22.7	13.7	5.1
Tibial stress syndrome	30.7	168.5	158.6	77.0	60.8	24.4	21.8	5.1	5.1
Achilles tendinopathy	40.7	171.1	156.9	82.5	63.6	25.4	23.1	14.5	5.1
Patellar tendinopathy	34.3	171.4	159.1	80.2	60.8	24.2	19.8	10.0	6.1
Gluteus medius injuries	36.2	187.0	158.1	72.7	60.2	22.0	21.7	10.1	4.3
Tibial stress fractures	32.3	170.4	156.9	76.6	57.5	23.8	20.3	7.6	6.1
Spinal injuries	39.6	168.0	154.7	74.8	56.6	23.9	21.5	12.9	6.4
Mean	36.2	171.3	158.5	77.1	60.3	24.0	21.6	10.2	5.4
Standard deviation	4.75	5.68	3.78	3.06	2.38	0.91	1.11	3.07	0.66

BMI, Body mass index; PFPS, patellar femoral pain syndrome; ITBFS, iliotibial band friction syndrome.

Regardless of activity level, women who develop PFPS have demonstrated associated hip abductor weakness, though the strength and direction of association is up for debate as seen in **Table 6**.

Table 6. Studies focusing on females with PFPS

Source & Publication date	Title of article	Population Age	Sample Size	Results
Baldon et al., 2009	Eccentric hip muscle function in females with and without patellofemoral pain syndrome	Ages 17-35	20 (10 PFPS & 10 control)	PFPS group showed lower peak torque of hip abductors as compared to controls
Bolgla et al., 2011	COMPARISON OF HIP AND KNEE STRENGTH AND NEUROMUSCULAR ACTIVITY IN SUBJECTS WITH AND WITHOUT PATELLOFEMORAL PAIN SYNDROME	Ages 18-30? (Mean age was 24.5)	36 (18 PFPS + 18 control)	Females with PFPS demonstrated less strength of the hip muscles
Cichanowski et al., 2007	Hip Strength in Collegiate Female Athletes with Patellofemoral Pain	Ages 18-25	26 (13 injured + 13 control)	Mean hip abductor force generated was less for injured athletes
Ireland et al., 2003	Hip strength in females with and without patellofemoral pain	Ages 12-21	30 (15 PFPS + 15 control)	PFPS group showed decreased hip abduction strength & decreased hip abductor rotation vs controls
Nunes et al., 2018	Hip rate of force development and strength are impaired in females with patellofemoral pain without signs of altered gluteus medius and maximus morphology	Ages 18-35	54 (27 PFPS + 27 controls)	PFPS group had slower rate of force development (RFD) for hip abductor muscles, 10% reduced isometric torque for hip abductor muscles
O'Sullivan et al., 2012	No Difference in Gluteus Medius Activation in Women With Mild Patellofemoral Pain	Ages 18-35	24 (12 PFPS + 12 control)	No significant differences in G-Med activation in healthy vs. injured
Plastaras et al., 2015	Is Hip Abduction Strength Asymmetry Present in Female Runners in the Early Stages of Patellofemoral Pain Syndrome?	Ages 18-45	57 (21 early PFPS + 36 control)	No significant differences in asymmetry found between early PFPS group and controls
Willson and Davis, 2009	Lower extremity strength and mechanics during jumping in women with patellofemoral pain	Ages 18-35	40 (20 PFPS + 20 control)	PFPS group had significantly reduced strength in trunk lateral flexion, hip abduction, & hip external rotation

Multiple studies have observed a correlation between women who currently have PFPS and having weaker hip abductor muscles than their non-injured peers (Baldon et al., 2009; Bolgla et al., 2011; Cichanowski et al., 2007; Ireland et al., 2003; Nunes et al., 2018). However, when looking prospectively, the gait mechanics and strength of the hip abductor muscles of novice female runners is not significantly different than their experienced counterparts. Mechanically, both experienced and inexperienced athletes run similarly, so experience alone does not predict risk for injury (Schmitz et al., 2014). Furthermore, when measuring the activation patterns of the GMed in females with PFPS compared to females without injury, the activation patterns were the same, so the force generated by the muscle for both groups should not differ significantly (O'Sullivan et al., 2012). When examining patients presenting with early signs of PFPS, the results did not line up with expectations; the subjects with early signs of PFPS did not show any significant difference between their hip abductor strength on the affected versus unaffected leg (Plastaras et al., 2016).

Both hip abductor strength asymmetry and overall weakness also have been implicated in females with conditions such as GT, Hip OA, Developmental Dysplasia of the Hip (DDH), and external snapping of the hip (Aepli- Schneider et al., 2012; Fearon et al., 2017; Leijendekkers et al., 2018; Jacobsen et al., 2012). In both GT and Hip OA, there is demonstrated bilateral hip abduction weakness as compared to controls. However, there is not a significant difference between the affected and unaffected leg in hip abduction strength; there is no significant evidence of strength asymmetry despite the unilateral presentation of patients with either condition (Fearon et al., 2017). An anatomical difference, such as a larger than normal femoral neck-shaft angle, could contribute to developing hip abductor weakness. In fact, in a group of healthy individuals, there was a modest association between the femoral neck-shaft angle and the amount of strength generated by the hip abductor muscles (Baggaley et al., 2015). However, downstream of that, the healthy individuals showed no significant signs of altered strength during motion, even with decreased hip abductor strength (Baggaley et al., 2015). In cases where GT has progressed to the point of needing surgical interventions, GMed tears are present, which could indicate that the destruction of the GMed lead to this progression (Aepli- Schneider et al., 2012). However, measuring these tears would be difficult without surgical intervention, so the degree of perceived pain could be used as a stand in for gaging the severity of GT (Fearon et al., 2017).

Males with Hip Abductor Weakness

The number hip abductor weakness studies performed on male-only cohorts was about half that were found on female-only cohorts, so studies which were a mix of both sexes but contained primarily male subjects are discussed in this section as well, as presented in **Table 7**.

Table 7. Studies focusing on males with hip abductor weakness

Source & Publication Date	Title of article	Gender	Population Age	Sample Size	Associated Syndrome	Results
Finnoff et al., 2011	Hip Strength and Knee Pain in High School Runners: A Prospective Study	Mixed, more males	Ages 14-18	98	PFPS & ITBS	Only 6 subjects developed PFPS, and 1 developed ITBS over the course of the study.
Fredericson et al., 2000	Hip abductor weakness in distance runners with iliotibial band syndrome	Mixed	Ages 18-41	54 (24 injured, 30 controls)	ITBS	Runners with ITBS have weaker hip abductors on the affected side & have weaker hip abductors than uninjured runners
Friel et al., 2006	Ipsilateral Hip Abductor Weakness After Inversion Ankle Sprain	Mixed	Ages 18-52	23	Ankle Sprains (chronic)	Hip abductor strength was slightly less on injured side vs non-injured side
Grau et al., 2007	Hip Abductor Weakness is not the Cause for Iliotibial Band Syndrome	Mixed, more males	Ages 18-50 (more males than females 7-3)	20 (10 ITBS + 10 controls)	ITBS	Differences in hip abductor strength between control group and ITBS group were not statistically significant
Habets et al., 2017	Hip muscle strength is decreased in middle-aged recreational male athletes with midportion Achilles tendinopathy: A cross-sectional study	Males	Ages 43-60	24 (12 with AT + 12 controls)	Achilles Tendinopathy (AT)	The AT group showed significantly less isometric strength in their hip abductors, external rotators, and extensors compared with the control group
McHugh et al., 2006	Risk Factors for Noncontact Ankle Sprains in High School Athletes: The Role of Hip Strength and Balance Ability	Mixed, more males	Ages 14-18	169 (101 male + 68 female)	Ankle Sprains	Hip abductor strength & balance weren't predictive of sustaining a non-contact ankle sprain

Nadler et al., 2002	The relationship between lower extremity injury and the hip abductor to extensor strength ratio in collegiate athletes	Mixed, more males	Ages 18-25	236 (162 males + 74 females)	HABD:Extension strength	Athletes with reported lower extremity injury had a different hip abduction to extension strength vs. those w/o injury; potentially due to hip extension weakness
Nepple et al., 2015	Hip Strength Deficits in Patients With Symptomatic Femoroacetabular Impingement and Labral Tears	Mixed, more males	Ages 18-50	50 (32 males + 18 females)	Femoroacetabular impingement (FAI)	Hip strength deficits were common in patients presenting with unilateral symptomatic FAI and occurred most commonly in hip abduction and flexion.
Noehren et al., 2014	Assessment of Strength, Flexibility, and Running Mechanics in Males with Iliotibial Band Syndrome	Males	Ages 18-45	34 (17 ITBS, 17 control)	ITBS	No hip abduction strength differences found between injured runners vs. controls
Zampagni et al., 2009	Can ankle imbalance be a risk factor for tensor fascia lata muscle weakness?	Males	Ages 18-40? (Mean 26 SD 6yrs)	29 (15 injured, 14 controls)	AIG (ankle imbalance)	Subjects with AIG had a weakness in the controlateral TFL muscle, with differences in force duration but not intensity

Hip abductor weakness is common even in elite athletes, occurring in as high of ratios as 50%, yet it has been shown to be easily corrected when given an at-home exercise set (Osborne et al., 2012). However, when this weakness is left unmonitored, it has been theorized that it can lead to additional injuries down the leg such as ITBS, PFPS, Femoroacetabular impingement (FAI), and various ankle injuries (Finnoff et al., 2011; Nepple et al., 2005; Zampagni et al., 2009).

In a large cross-sectional study, it was found that there is not a significant relationship between the strength of hip abduction and the general kinematics of the lower leg during a run. For measurements, this study used isokinetic contraction as a way to gage the hip abduction strength, and a pressure-sensitive treadmill to gage hip and knee movements. The use of such a treadmill, while providing information about force of the foot-strike, cannot properly capture the mid-stride form, that is how the leg travels through the air from the time it pushes off the ground to the time it strikes the ground in front of the subject, and is of limited information if trying to measure hip abductor muscle activity during all parts of ambulation (Brund et al., 2017).

The majority of injury focus has been on ITBS because it’s one of the most common overuse injury in athletics, especially in running sports (Grau et al., 2008). For male athletes, the association between hip abductor muscle weakness and subsequent ITBS is not clear-cut. In one study, male runners with ITBS were found to have weaker hip abductors on the affected limb, and to have overall weaker hip abductors than runners who were not affected with ITBS (Fredericson et al., 2000). However, other more recent studies have shown that runners with ITBS do not have significantly weaker hip abductor muscles on their injured leg as compared to their non-injured leg nor do that have weaker hip abductor muscles compared to controls (Grau et al., 2008). While these studies’ results contradict one another, the both looked at ITBS retrospectively rather than prospectively, so the cause-effect relationship of hip abductor weakness preceding ITBS is not strongly established (Fredericson et al., 2000; Grau et al., 2008).

Another common point of injury for males, potentially as a result of hip abductor weakness, is the ankle joint. Studies on both ankle imbalance and chronic ankle sprains have demonstrated that hip abductor weakness could develop after an ankle sprain either on the same side or on the contralateral side (Friel et al., 2006; Zampagni et al., 2009). The measurement of strength was based on overall torque generated by the muscle group as a unit, rather than from each hip abductor, so the muscle that generated the force, or was not generating enough force, was not specified (Friel et al., 2006). Another caveat to this result is the fact that the intensity of the force generated was comparable to the non-injured athlete, but the duration of the force generated was shorter, so endurance was the main aspect lost after suffering an ankle injury (Zampagni et al., 2009). Additionally, when studied prospectively, weak hip abductor muscles were not implicated in developing non-contact ankle sprains, but the samples in the previous two studies were older, which could have contributed to the increased resilience or the decreased rate of occurrence of ankle sprains in this study in general (McHugh et al., 2006).

DISCUSSION

From the presented studies, a few key points come to light. First, hip abductor weakness has been repeatedly connected to injuries manifesting themselves at four sites on the lower limb: the acetabulofemoral joint, the lateral femur, the patellofemoral joint, and the ankle joint. Injuries in the acetabulofemoral range from GT, hip OA, femoral acetabular impingement (FAI), DDH, and external snapping hip (Fearon et al., 2017; Zacharias et al., 2016; Nepple et al., 2015; Leijendekkers et al., 2018; Jacobsen et al., 2012). ITBS is the most common injury at the lateral femur that is also connected to hip abductor weakness (Taunton et al., 2002; Fredericson et al., 2000). The most cited and discussed patellofemoral joint injury is PFPS, which has a more nuanced relationship between hip abductor weakness and the resulting injury (Taunton et al., 2002; Ireland 2003; Plastaras et al., 2016). Injuries at the ankle joint due to hip abductor weakness are mainly seen in younger populations and are more associated with chronic ankle sprains rather than one instance (Friel et al., 2006; Zampagni et al., 2009).

When examining the incidences of these injuries in males versus females, it seems as though by just the volume of studies done that males tend to sustain injuries at the lateral femur and the ankle joint and females tend to sustain injuries at the hip joint and the patellofemoral joint. These differences could be explained by difference in gait mechanics between the sexes, or participation in different activities making one sex more susceptible to various injuries (Bailey et al., 2018).

In comparing types of injuries between older versus younger populations, it seems as though younger populations sustain more overuse injuries such as ITBS and PFPS and older populations tend to sustain injuries due to atrophy of the muscles (Taunton et al., 2002; Zacharias et al., 2018). However, there has not been a study done comparing injury prevalence between young and old subjects of similar activity levels, nor has there been a study connecting hip abductor weakness to said prevalence. Furthermore, there is limited information on the etiology of hip OA for patients in a younger age group, and the data using EMG is largely focused on the gait of a younger population, so the direct comparisons are not readily available for examination. The following sections will take a closer look behind the differences in injury prevalence and the strength of that relationship to hip abductor weakness, as well as gait patterns observed in males versus females. Additionally, the difference between the ways injuries manifest themselves in younger versus older populations will be discussed in more detail.

Points of injury in males versus females

In terms of volume of research, more studies have focused on hip abductor weakness and the subsequent manifestations, such as PFPS and ITBS, in female populations than in male populations (Foch et al., 2015; Bolgla et al., 2011). At first glance it seems as though females are more prone to injuries connected to hip abductor weakness as compared to males, but this is without taking to account the underlying differences of gait mechanics between males and females at baseline (Taunton et al., 2002).

Studies have shown that when females perform dynamic movements such as jumping, they show larger amounts of knee abduction upon landing when compared to males. Weaker hip abductors, regardless of sex, leads to higher knee abduction angles

(Howard et al., 2011). This could point to there being a threshold abduction angle that when the subject goes beyond, regardless of sex, indicates hip abductor weakness and greater tendency for injury. Alternatively, the percent change in knee abduction angle, based on the sex of the subject, could be a better indicator for risk for injury, and could also indicate the presence of hip abductor weakness. Whether there is an absolute angle of knee abduction that indicates greater risk of injury, or if there is a percent change in that angle that signals hip abductor weakness and predisposition for injury is unclear, but both theories seem plausible and could be grounds for further investigation. Additionally, the relationship between the degree of weakness in the hip abductor muscles and the degree of change in landing mechanics is both variable between subjects and is not a predictable linear relationship, at least according to the present findings.

The current evidence suggests that there exists an absolute knee abduction angle that indicates hip abductor weakness. This is supported by the fact that females already have a larger knee abduction angle upon landing when non-injured. By this line of reasoning, because females are closer to the knee abduction angle that occurs when a subject has hip abductor weakness, they are more susceptible to injuries even with a minor decrease in hip abductor strength as compared to males who have a similar decrease in hip abductor strength. This potential causal relationship between hip abductor weakness, knee abduction angle, and probability of injury is still unclear, and further research in this subject could shed light on this complex relationship.

In healthy subjects, it's been shown that there are two sets of gait patterns, not dependent on sex, and one pattern has a larger frontal plane projection angle of the knee than the other (Phinyomark et al., 2015). This increased frontal plane projection angle has also been linked to female runners who have PFPS and hip abductor weakness, but in healthy runners, a higher frontal plane projection angle has been connected to increased hip abduction strength (Leão et al., 2016). However, when studying the gait patterns of subjects with PFPS, the data has shown that while injured males have one homogeneous gait pattern, females can be divided into two gait patterns, yet both have underlying PFPS (Watari et al., 2018). This study measured pelvic acceleration rather than muscle torque, so while it captured the overall motions, it did not capture the activation patterns and force generation of the muscles used while running. One could infer that because there were two distinct gait patterns, there could be two different changes in a person's gait that that lead to the development of PFPS. Either gait pattern could develop as a result of hip abductor weakness, or either gait pattern could then lead to hip abductor weakness, but the current results leave this causal relationship up for exploration.

In males, it has been shown that weak hip abductors lead to greater hip and knee contact forces during walking (Valente et al., 2013). If the GMed is weakened, walking impact forces are transferred to the GMax, located superficially to the GMed, and the Rectus Femoris, located anterior & medially to the GMed and the TFL, as seen in **Figure 3 and 4.**

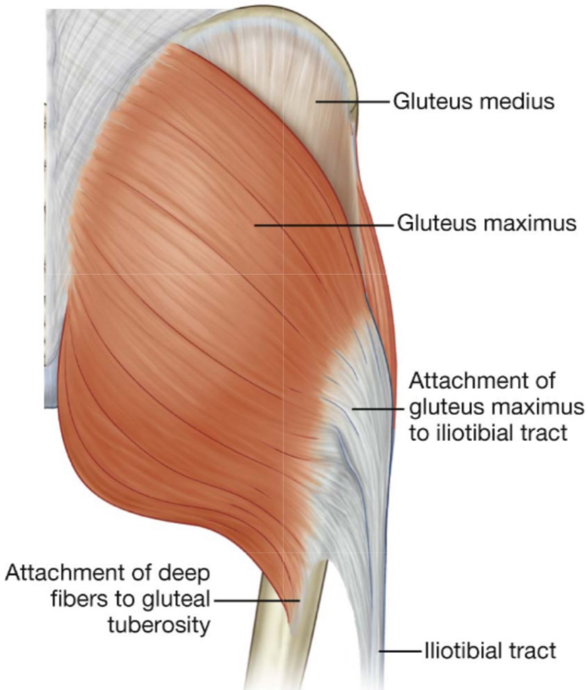

Figure 3. Posterior view of the gluteal region. As shown, one can see the GMax & its superficial position to the GMed. Taken from (Gray's Basic Anatomy, 2012)

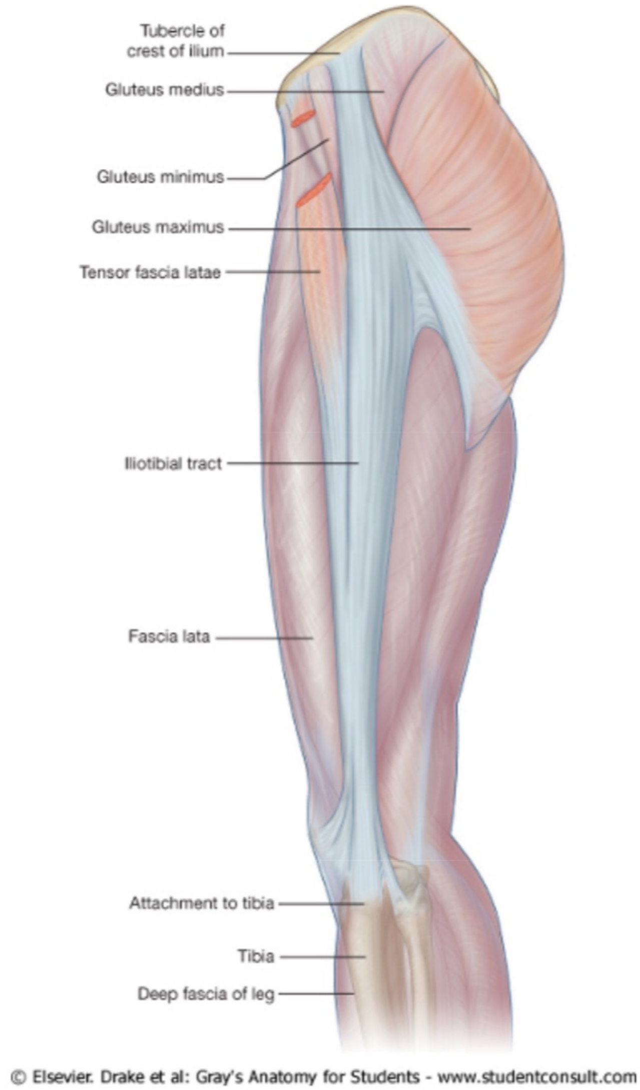

Figure 4. Lateral view of the leg. The relationship between the TFL, the GMed, and the GMax are shown here. Not indicated is the rectus femoris, which is anterior to the hip abductor muscles and deep to the Fascia Lata. Taken from (Gray's Basic Anatomy 2012)

Additionally, the increased knee contact forces with a weakened GMed can transfer to the gastrocnemius (Valente et al., 2013). These force transfers, which leads to an increased load on the GMax, Rectus Femoris, and gastrocnemius, could be a possible cause for the increased tendency for males to experience lateral thigh injuries, such as ITBS, and ankle-related injuries, such as Achilles tendinopathy (Noehren et al., 2014; Habets et al., 2017). Though the overall injury incidence is observed to be higher in females even at a young age, the prevalence of such injuries in males who are active could be due to the gait alterations in the presence of GMed weakness (Taunton et al., 2002; Stracciolini et al., 2014).

Another interesting point with regards to females and gait mechanics is the fact that hip abductor weakness is connected to gait patterns that suggest both an increase and a decrease in trunk lateral flexion. Females with PFPS demonstrated a decrease in trunk lateral flexion force, but females with ITBS demonstrated an increase in trunk lateral flexion force (Willson et al., 2009; Foch et al., 2015). This is interesting because both pathologies have been associated with hip abductor weakness, yet it is producing two different gait mechanics either due to compensation, or possibly due to over-strengthening of another muscle group. If it is assumed that hip abductor weakness is at the root of both ITBS and PFPS, then there must be another intermediate compensation or activation of another muscle group in order to produce the opposite mechanics. Or, if hip abductor weakness is the result of PFPS or ITBS, that still would not explain the opposite mechanics. Possible solutions to this dilemma could be to either have a more comprehensive measurement of gait mechanics by adding additional EMG markers on the body to more accurately measure motions, or to collect more isometric muscle contraction measurements on all of the thigh muscles and the muscles of the core as well. This would provide a more comprehensive picture as to if this is just GMed or TFL weakness, or if this weakness is combined with an imbalance of strength elsewhere.

Lastly only females with a low BMI were more susceptible to overuse injuries, whereas there was no significant correlation between BMI and injury rate in males (Taunton et al., 2002). Since BMI differences have been linked to various health risks, it is imperative to eliminate BMI differences as a confounding variable in any study examining gait mechanics, muscle weakness, and injury susceptibility. With this added piece of information, studies with significant differences in BMI between two groups should be examined more thoroughly in order to avoid confounding the data (Cooper et al., 2016).

Hip OA and other pathologies of the hip in younger versus older populations

When comparing the influence of hip abductor weakness on conditions related to the hip joint, it is important to consider the age of the population being studied. For example, in an older population, females with unilateral hip OA have demonstrated slower walking, lower cadence in their gait, and a decreased duration of single leg stance on the affected leg (Fearon et al., 2017). Whereas in younger females with external snapping of the hip, there is demonstrated less activation of the GMed, yet the gait pattern remains unaffected (Jacobsen et al., 2013). Where there is significant weakness yet no gait mechanical change, it could be inferred that there is recruitment of other muscle groups in order to compensate for the weakness.

Another possible sequence of events leading to this GMed weakness appearing in these conditions could be the initial over-activation of certain muscle groups, thereby reducing the need to use the GMed and other hip abductors, which then results in atrophy of the hip abductor muscles. One possible muscle group that could be recruited for motion is the core muscles, as seen in the increased tendency for ipsilateral trunk flexion in patients with DDH (Leijendekkers et al., 2018). This overactivity could be due to the increased relative strength as compared to the hip abductors, causing the trunk muscles to over compensate even if there is just a slight relative weakness in the hip abductors. The subsequent atrophy of the hip abductor muscles has been observed in cases of later stages of hip OA, and this decreased muscle mass would result in the decreased ability to generate adequate force, should it be required (Zacharias et al., 2016; Zacharias et al., 2018). This decreased muscle mass could explain the observed increase in neural activation because one would need to activate a larger percentage of the muscle to produce the same motion with the same force if the muscle is smaller.

CONCLUSIONS AND FUTURE DIRECTIONS

The scope of literature presented on the relationship between hip abductor weakness and the various lower limb injuries associated with it has illuminated some interesting points. While the connection between females with hip abductor weakness and resultant PFPS appears causal, the connection between males with hip abductor weakness and PFPS is less clear. Additionally, the relationship between ITBS and hip abductor weakness depending on age, and sex is still difficult to ascertain due to the majority of studies being performed cross-sectionally and retrospectively, rather than longitudinally and prospectively.

In order to create a stronger argument for a causal relationship, more longitudinal studies need to be done on a population either of the same sex, or of similar age range. This can be accomplished by recruiting cohorts at the beginning of a sports season, if aiming to measure probability of injury in relationship to hip abductor weakness, or by recruiting a homogenous group of subjects and then dividing them into injured versus non-injured subjects as the study progresses. In this way, the research can track changes in muscle strength based on the subject, rather than attempting to find a close enough subject to pair with as a control. This also reduces the tendency to exclude a subject who has previously sustained an injury, which could provide critical information as to how a previously injured subject progresses throughout the study. These longitudinal studies also make it easier to keep the data from subjects whose injury status changes over the course of the study. The inclusion of these subjects can provide multiple lenses with which to look at the new data and could illuminate associations between injury and hip abductor weakness that were previously underexamined.

Additionally, future research should not sort the population into weak versus strong hip abductors until after the study is over. This would help to avoid the error of creating experimenter bias between the two groups, even if the study is done in a double-blind manner. Not only would this help avoid confirmation bias when trying to assess the association between hip abductor weakness and these resultant pathologies, but this also could avoid the over-emphasis of hip abductor weakness being the cause of these pathologies rather than an effect that is observed with these injuries. Because it is still unclear if hip abductor weakness is the first change observed in the subject – before gait mechanic changes, and before the subsequent pathologies – it would be beneficial to observe how these changes come about over a period of time, rather than looking back after injury and weakness have already occurred.

Another point of note is that future research should focus on the differences in gait kinematics between males and females of similar ages and activity levels. This can help create a standard for which deviations from the "normal range" can be established. By creating a standardized library of which muscles are active during which phases of the gait in males and females, health professionals can more accurately diagnose what is deviant from the normal. This would help in the delivery of more personalized care in both rehabilitation and prevention of injuries.

If there are established differences of the gait mechanics between the sexes, the rehabilitation protocols can become more effective in addressing the underlying issue.

For example, it has been shown that both a core-based and hip-based rehabilitation protocol are both effective at increasing strength in the hip abductors, but in males specifically these programs have shown to increase their hip-extensor strength as well (Bolgla et al., 2016). Knowing if other muscle groups needed to be strengthened, in addition to the hip abductors, would help to create a more balanced rehabilitation program, which could protect from injury recurrence.

The hip abductor muscles are involved in stabilizing the hip and the entire lower limb. Maintaining their strength is crucial for maintaining ease of mobility as a person ages. It is therefore critical to continue to examine the connection between hip abductor weakness and gait-related pathologies so that more effective rehabilitation and injury prevention programs can be put in place for a better quality of life.

REFERENCES

Aepli-Schneider, N., Treumann, T., Müller, U., & Schmid, L. (2012). Degenerative Ruptur der Hüftabduktoren. *Zeitschrift für Rheumatologie*, *71*(1), 68–74. https://doi.org/10.1007/s00393-011-0919-y

Arden, N., & Nevitt, M. C. (2006). Osteoarthritis: Epidemiology. *Best Practice & Research Clinical Rheumatology*, *20*(1), 3–25. https://doi.org/10.1016/j.berh.2005.09.007

Arnold, M. J., & Moody, A. L. (2018). Common Running Injuries: Evaluation and Management. *American Family Physician*, *97*(8), 510–516.

Baggaley, M., Noehren, B., Clasey, J. L., Shapiro, R., & Pohl, M. B. (2015). Frontal plane kinematics of the hip during running: Are they related to hip anatomy and strength? Gait & Posture, 42(4), 505–510. https://doi.org/10.1016/j.gaitpost.2015.07.064

Bailey, C. A., Corona, F., Pilloni, G., Porta, M., Fastame, M. C., Hitchcott, P. K., … Côté, J. N. (2018). Sex-dependent and sex-independent muscle activation patterns in adult gait as a function of age. *Experimental Gerontology*, *110*, 1–8. https://doi.org/10.1016/j.exger.2018.05.005

Baldon, R. de M., Nakagawa, T. H., Muniz, T. B., Amorim, C. F., Maciel, C. D., & Serrão, F. V. (2009). Eccentric hip muscle function in females with and without patellofemoral pain syndrome. *Journal of Athletic Training*, *44*(5), 490–496. https://doi.org/10.4085/1062-6050-44.5.490

Barbosa, A. C., Carvalho, R. A. N., Bonifácio, D. N., Martins, F. L. M., & Barbosa, M. C. S. A. (2016). Increased Activation Amplitude Levels of Gluteus Medius in Women During Isometric and Dynamic Conditions Following a 4-week Protocol of Low-load Eccentric Exercises. *Physiotherapy Research International*, *21*(4), 257–263. https://doi.org/10.1002/pri.1643

Bewyer, K. J., Bewyer, D. C., Messenger, D., & Kennedy, C. M. (2009). PILOT DATA: ASSOCIATION BETWEEN GLUTEUS MEDIUS WEAKNESS AND LOW BACK PAIN DURING PREGNANCY. *The Iowa Orthopaedic Journal*, *29*, 97–99.

Bolgla, L. A., Malone, T. R., Umberger, B. R., & Uhl, T. L. (2011). COMPARISON OF HIP AND KNEE STRENGTH AND NEUROMUSCULAR ACTIVITY IN SUBJECTS WITH AND WITHOUT PATELLOFEMORAL PAIN SYNDROME. *International Journal of Sports Physical Therapy*, *6*(4), 285–296.

Bolgla, L. A., Earl-Boehm, J., Emery, C., Hamstra-Wright, K., & Ferber, R. (2016). PAIN, FUNCTION, AND STRENGTH OUTCOMES FOR MALES AND FEMALES WITH PATELLOFEMORAL PAIN WHO PARTICIPATE IN EITHER A HIP/CORE- OR KNEE-BASED REHABILITATION PROGRAM. *International Journal of Sports Physical Therapy*, *11*(6), 926–935.

Boling, M. C., Padua, D. A., & Alexander Creighton, R. (2009). Concentric and Eccentric Torque of the Hip Musculature in Individuals With and Without Patellofemoral Pain. Journal of Athletic Training, 44(1), 7–13.

Brown, A. M., Zifchock, R. A., Hillstrom, H. J., Song, J., & Tucker, C. A. (2016). The effects of fatigue on lower extremity kinematics, kinetics and joint coupling in symptomatic female runners with iliotibial band syndrome. *Clinical Biomechanics*, *39*, 84–90. https://doi.org/10.1016/j.clinbiomech.2016.09.012

Brund, R. B. K., Rasmussen, S., Nielsen, R. O., Kersting, U. G., Laessoe, U., & Voigt, M. (2017). The association between eccentric hip abduction strength and hip and knee angular movements in recreational male runners: An explorative study. *Scandinavian Journal of Medicine & Science in Sports*, *28*(2), 473–478. https://doi.org/10.1111/sms.12923

Cichanowski, H. R., Schmitt, J. S., Johnson, R. J., & Niemuth, P. E. (2007). Hip Strength in Collegiate Female Athletes with Patellofemoral Pain. *Medicine & Science in Sports & Exercise*, *39*(8), 1227–1232. https://doi.org/10.1249/mss.0b013e3180601109

Cooper, N. A., Scavo, K. M., Strickland, K. J., Tipayamongkol, N., Nicholson, J. D., Bewyer, D. C., & Sluka, K. A. (2016). Prevalence of gluteus medius weakness in people with chronic low back pain compared to healthy controls. *European Spine Journal: Official Publication of the European Spine Society, the European Spinal Deformity Society, and the European Section of the Cervical Spine Research Society*, *25*(4), 1258–1265. https://doi.org/10.1007/s00586-015-4027-6

Dierks, T. A., Manal, K. T., Hamill, J., & Davis, I. S. (2008). Proximal and distal influences on hip and knee kinematics in runners with patellofemoral pain during a prolonged run. *The Journal of Orthopaedic and Sports Physical Therapy*, *38*(8), 448–456. https://doi.org/10.2519/jospt.2008.2490

Drake, R., Vogl, A. W., & Mitchell, A. W. M. (2012). Regional Anatomy: Gluteal Region | Gray's Basic Anatomy | Lower Limb. Retrieved June 12, 2018, from https://studentconsult.inkling.com/read/grays-basic-anatomy-drake-vogl-mitchell-1st/chapter-6/regional-anatomy-gluteal-region

Fairclough, J., Hayashi, K., Toumi, H., Lyons, K., Bydder, G., Phillips, N., … Benjamin, M. (2006). The functional anatomy of the iliotibial band during flexion and extension of the knee: implications for understanding iliotibial band syndrome. *Journal of Anatomy*, *208*(3), 309–316. https://doi.org/10.1111/j.1469-7580.2006.00531.x

Fearon, A., Neeman, T., Smith, P., Scarvell, J., & Cook, J. (2017). Pain, not structural impairments may explain activity limitations in people with gluteal tendinopathy or hip osteoarthritis: A cross sectional study. *Gait & Posture*, *52*, 237–243. https://doi.org/10.1016/j.gaitpost.2016.12.005

Finnoff, J. T., Hall, M. M., Kyle, K., Krause, D. A., Lai, J., & Smith, J. (2011). Hip Strength and Knee Pain in High School Runners: A Prospective Study. *PM&R*, *3*(9), 792–801. https://doi.org/10.1016/j.pmrj.2011.04.007

Flack, N. A. M. S., Nicholson, H. D., & Woodley, S. J. (2012). A review of the anatomy of the hip abductor muscles, gluteus medius, gluteus minimus, and tensor fascia lata. *Clinical Anatomy*, *25*(6), 697–708. https://doi.org/10.1002/ca.22004

Flack N.A.M.S., Nicholson H.D., & Woodley S.J. (2014). The anatomy of the hip abductor muscles. *Clinical Anatomy*, *27*(2), 241–253. https://doi.org/10.1002/ca.22248

Flaxman, T. E., Smith, A. J. J., & Benoit, D. L. (2014). Sex-Related Differences in Neuromuscular Control: Implications for Injury Mechanisms or Healthy Stabilisation Strategies? *Journal of Orthopaedic Research*, *32*(2), 310–317. https://doi.org/10.1002/jor.22510

Foch, E., Reinbolt, J. A., Zhang, S., Fitzhugh, E. C., & Milner, C. E. (2015). Associations between iliotibial band injury status and running biomechanics in women. *Gait & Posture*, *41*(2), 706–710. https://doi.org/10.1016/j.gaitpost.2015.01.031

Fredericson, M., Cookingham, C. L., Chaudhari, A. M., Dowdell, B. C., Oestreicher, N., & Sahrmann, S. A. (2000). Hip abductor weakness in distance runners with iliotibial band syndrome. *Clinical Journal of Sport Medicine: Official Journal of the Canadian Academy of Sport Medicine*, *10*(3), 169–175.

Friel, K., McLean, N., Myers, C., & Caceres, M. (2006). Ipsilateral Hip Abductor Weakness After Inversion Ankle Sprain. *Journal of Athletic Training; Dallas*, *41*(1), 74–78.

Gottschalk, F., Kourosh, S., & Leveau, B. (1989). The functional anatomy of tensor fasciae latae and gluteus medius and minimus. *Journal of Anatomy*, *166*, 179–189.

Grau, S., Krauss, I., Maiwald, C., Best, R., & Horstmann, T. (2008). Hip abductor weakness is not the cause for iliotibial band syndrome. *International Journal of Sports Medicine*, *29*(7), 579–583. https://doi.org/10.1055/s-2007-989323

Habets, B., Smits, H. W., Backx, F. J. G., van Cingel, R. E. H., & Huisstede, B. M. A. (2017). Hip muscle strength is decreased in middle-aged recreational male athletes with midportion Achilles tendinopathy: A cross-sectional study. *Physical Therapy in Sport*, *25*, 55–61. https://doi.org/10.1016/j.ptsp.2016.09.008

Hamill, J., Miller, R., Noehren, B., & Davis, I. (2008). A prospective study of iliotibial band strain in runners. *Clinical Biomechanics*, *23*(8), 1018–1025. https://doi.org/10.1016/j.clinbiomech.2008.04.017

Howard, J. S., Fazio, M. A., Mattacola, C. G., Uhl, T. L., & Jacobs, C. A. (2011). Structure, Sex, and Strength and Knee and Hip Kinematics During Landing. *Journal of Athletic Training*, *46*(4), 376–385.

Image: Gluteus maximus muscle. Posterior view. | Gray's Basic Anatomy. (2012). Retrieved June 12, 2018, from https://studentconsult.inkling.com/read/grays-basic-anatomy-drake-vogl-mitchell-1st/chapter-6/figure-6-29

Image | Gray's Basic Anatomy | Learning Resources | Iliotibial Band…. (2012). Retrieved June 12, 2018, from https://studentconsult.inkling.com/read/grays-basic-anatomy-drake-vogl-mitchell-1st/learning-resources/figure-86

Ireland, M. L., Willson, J. D., Ballantyne, B. T., & Davis, I. M. (2003). Hip strength in females with and without patellofemoral pain. *The Journal of Orthopaedic and Sports Physical Therapy*, *33*(11), 671–676. https://doi.org/10.2519/jospt.2003.33.11.671

Jacobsen, J. S., Thorborg, K., Søballe, K., & Ulrich-Vinther, M. (2012). Eccentric hip abductor weakness in patients with symptomatic external snapping hip. *Scandinavian Journal of Medicine & Science in Sports*, *22*(6), e140–e146. https://doi.org/10.1111/j.1600-0838.2012.01525.x

Jacobsen, J. S., Kersting, U. G., Rathleff, M. S., Simonsen, O., Søballe, K., & Ulrich, M. (2013). The gait pattern is not impaired in subjects with external snapping hip: a comparative cross-sectional study. *BMC Musculoskeletal Disorders*, *14*, 212. https://doi.org/10.1186/1471-2474-14-212

Leão Almeida, G. P., de Moura Campos Carvalho e Silva, A. P., Renovato França, F. J., Oliveira Magalhães, M., Nogueira Burke, T., & Pasqual Marques, A. (2016). Relationship between frontal plane projection angle of the knee and hip and trunk strength in women with and without patellofemoral pain. *Journal of Back &*

Musculoskeletal Rehabilitation, *29*(2), 259–266. https://doi.org/10.3233/BMR-150622

Leijendekkers, R. A., Marra, M. A., Kolk, S., van Bon, G., Schreurs, B. W., Weerdesteyn, V., & Verdonschot, N. (2018). Gait symmetry and hip strength in women with developmental dysplasia following hip arthroplasty compared to healthy subjects: A cross-sectional study. *PLoS ONE*, *13*(2). https://doi.org/10.1371/journal.pone.0193487

McHugh, M. P., Tyler, T. F., Tetro, D. T., Mullaney, M. J., & Nicholas, S. J. (2006). Risk Factors for Noncontact Ankle Sprains in High School Athletes: The Role of Hip Strength and Balance Ability. *The American Journal of Sports Medicine*, *34*(3), 464–470. https://doi.org/10.1177/0363546505280427

Nepple, J. J., Goljan, P., Briggs, K. K., Garvey, S. E., Ryan, M., & Philippon, M. J. (2015). Hip Strength Deficits in Patients With Symptomatic Femoroacetabular Impingement and Labral Tears. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, *31*(11), 2106–2111. https://doi.org/10.1016/j.arthro.2015.04.095

Noehren, B., Schmitz, A., Hempel, R., Westlake, C., & Black, W. (2014). Assessment of Strength, Flexibility, and Running Mechanics in Males with Iliotibial Band Syndrome. *The Journal of Orthopaedic and Sports Physical Therapy*, *44*(3), 217–222. https://doi.org/10.2519/jospt.2014.4991

Nunes, G. S., Barton, C. J., & Serrão, F. V. (2018). Hip rate of force development and strength are impaired in females with patellofemoral pain without signs of altered gluteus medius and maximus morphology. *Journal of Science and Medicine in Sport*, *21*(2), 123–128. https://doi.org/10.1016/j.jsams.2017.05.014

Osborne, H. R., Quinlan, J. F., & Allison, G. T. (2012). Hip abduction weakness in elite junior footballers is common but easy to correct quickly: a prospective sports team cohort based study. *Sports Medicine, Arthroscopy, Rehabilitation, Therapy & Technology: SMARTT*, *4*(1), 37. https://doi.org/10.1186/1758-2555-4-37

O'Sullivan, K., Herbert, E., Sainsbury, D., McCreesh, K., & Clifford, A. (2012). No Difference in Gluteus Medius Activation in Women With Mild Patellofemoral Pain. *Journal of Sport Rehabilitation*, *21*(2), 110–118. https://doi.org/10.1123/jsr.21.2.110

Phinyomark, A., Osis, S., Hettinga, B. A., & Ferber, R. (2015). Kinematic gait patterns in healthy runners: A hierarchical cluster analysis. *Journal of Biomechanics*, *48*(14), 3897–3904. https://doi.org/10.1016/j.jbiomech.2015.09.025

Piva, S. R., Goodnite, E. A., & Childs, J. D. (2005). Strength around the hip and f lexibility of soft tissues in individuals with and without patellofemoral pain syndrome. *The Journal of Orthopaedic and Sports Physical Therapy*, *35*(12), 793–801. https://doi.org/10.2519/jospt.2005.35.12.793

Plastaras, C., McCormick, Z., Nguyen, C., Rho, M., Nack, S. H., Roth, D., … Caldera, F. (2016). Is Hip Abduction Strength Asymmetry Present in Female Runners in the Early Stages of Patellofemoral Pain Syndrome? *The American Journal of Sports Medicine*, *44*(1), 105–112. https://doi.org/10.1177/0363546515611632

Schmitz, A., Russo, K., Edwards, L., & Noehren, B. (2014). Do novice runners have weak hips and bad running form? *Gait & Posture*, *40*(1), 82–86. https://doi.org/10.1016/j.gaitpost.2014.02.014

Segal, N. A., Felson, D. T., Torner, J. C., Zhu, Y., Curtis, J. R., Niu, J., & Nevitt, M. C. (2007). Greater Trochanteric Pain Syndrome: Epidemiology and Associated Factors. *Archives of Physical Medicine and Rehabilitation*, *88*(8), 988–992. https://doi.org/10.1016/j.apmr.2007.04.014

Stracciolini, A., Casciano, R., Levey Friedman, H., Stein, C. J., Meehan, W. P., & Micheli, L. J. (2014). Pediatric Sports Injuries: A Comparison of Males Versus Females. *The American Journal of Sports Medicine*, *42*(4), 965–972. https://doi.org/10.1177/0363546514522393

Su, C. A., Kusin, D. J., Li, S. Q., Ahn, U. M., & Ahn, N. U. (2018). The Association Between Body Mass Index and the Prevalence, Severity, and Frequency of Low Back Pain: Data From the Osteoarthritis Initiative. *Spine*, *43*(12), 848–852. https://doi.org/10.1097/BRS.0000000000002601

Taunton, J. E., Ryan, M. B., Clement, D. B., McKenzie, D. C., Lloyd-Smith, D. R., & Zumbo, B. D. (2002). A retrospective case-control analysis of 2002 running injuries. *British Journal of Sports Medicine, 36*(2), 95–101. https://doi.org/10.1136/bjsm.36.2.95

Valente, G., Taddei, F., & Jonkers, I. (2013). Influence of weak hip abductor muscles on joint contact forces during normal walking: probabilistic modeling analysis. *Journal of Biomechanics*, *46*(13), 2186–2193. https://doi.org/10.1016/j.jbiomech.2013.06.030

Watari, R., Osis, S. T., Phinyomark, A., & Ferber, R. (2018). Runners with patellofemoral pain demonstrate sub-groups of pelvic acceleration profiles using hierarchical cluster analysis: an exploratory cross-sectional study. *BMC Musculoskeletal Disorders*, *19*(1), 120. https://doi.org/10.1186/s12891-018-2045-3

Willson, J. D., & Davis, I. S. (2009). Lower Extremity Strength and Mechanics during Jumping in Women with Patellofemoral Pain. *Journal of Sport Rehabilitation*, *18*(1), 76–90. https://doi.org/10.1123/jsr.18.1.76

Zacharias, A., Pizzari, T., English, D. J., Kapakoulakis, T., & Green, R. A. (2016). Hip abductor muscle volume in hip osteoarthritis and matched controls. *Osteoarthritis and Cartilage*, *24*(10), 1727–1735. https://doi.org/10.1016/j.joca.2016.05.002

Zacharias, A., Green, R. A., Semciw, A., English, D. J., Kapakoulakis, T., & Pizzari, T. (2018). Atrophy of hip abductor muscles is related to clinical severity in a hip osteoarthritis population. *Clinical Anatomy*, *31*(4), 507–513. https://doi.org/10.1002/ca.23064

Zampagni, M. L., Corazza, I., Molgora, A. P., & Marcacci, M. (2009). Can ankle imbalance be a risk factor for tensor fascia lata muscle weakness? *Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology*, *19*(4), 651–659. https://doi.org/10.1016/j.jelekin.2008.03.006

CURRICULUM VITAE

[redacted]